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Experimental investigation of the high-temperature air heating effect on the model artificial gas combustion process

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Abstract. A description of the experimental rig is presented. The effect of combustion air high-temperature (up to 800°C) heating on the model artificial gas combustion process is described. The model artificial gas is a CO-N_2 mixture. A comparison of the premixed and diffusion flame lower explosive limits is carried out. Experimental data are compared with open access published data of production of artificial gas-fired CCPP.

1. Introduction

Carbon monoxide (CO) is the main combustible component of the majority artificial gas fuels. Syngas of the air- and oxygen-blown coal gasification, as well as by-products of various technological processes («industrial gases», most often blast-furnace gas [1]) belongs to the artificial gas fuels of both the simple and combined (CCPP) gas turbine cycles. The CO content in air-blown coal gasification raw syngas (at the gasifier outlet) is 15÷30 vol.%, the CO content in oxygen-blown coal gasification raw syngas is 35÷65 vol.%, the CO content in industrial gases is about 10÷65 vol.%.

A main way to increase the gas turbine cycle economic and energy parameters is to increase the gas turbine inlet flow (gas turbine working fluid) pressure and temperature. An increase in the air compression ratio is accompanied by an increase in air temperature, which reaches about 400÷500°C at the present day. In perspective, the variants of high-temperature (up to 800÷900°C) heating of gas turbine fuel combustion air are considered [2]. Therefore, the investigation of the gas fuel combustion process in a high-temperature (800÷900°C) air flow becomes a crucial task.

The relevance of investigation of CO combustion is also justified by its low reactivity, which causes a restriction in the low-calorie artificial gas combustion technologies application.

In this paper, we investigate the effect of combustion air high-temperature (up to 800°C) heating on the model artificial gas fuel (CO-N_2 mixture) diffusion flame lower extinction limit and gas fuel critical lower heating value.

2. Method

The experimental rig is based on the microflow fuel gas diffusion combustion in a co-current airflow. This flame configuration is similar to the actual gas turbine burner configurations of leading concerns-manufactured (such as General Electric and Mitsubishi Hitachi Power Systems [3, 4]).

The experimental rig has been developed to investigate the model artificial gas fuel (CO-N_2 mixture) combustion process in high-temperature (up to 800°C) co-current airflow. The general flow diagram of the experimental rig is presented in figure 1.

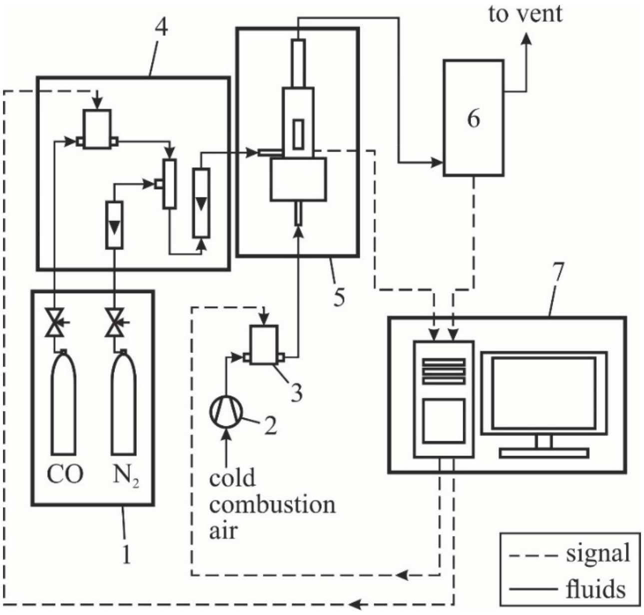


Figure 1 – General flow diagram of the experimental rig: 1 – gaseous CO and N_2 tanks; 2 – air compressor; 3 – RRG-12-type flow controller; 4 – model artificial gas (CO-N_2 mixture) preparation system; 5 – module for investigation of the model artificial gas combustion process; 6 – products of model artificial gas combustion analysis system; 7 – data acquisition and control system.

Figure 2 shows the scheme of the module for investigation of the model artificial gas combustion process.

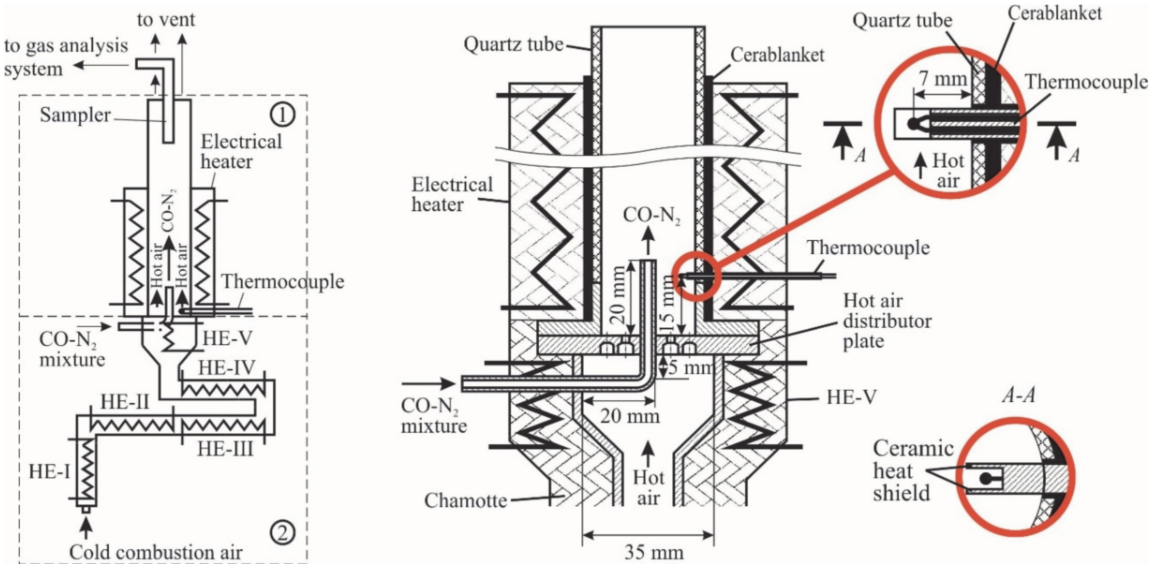


Figure 2 – The module (a) and the reaction chamber (b) schemes: 1 – the reaction chamber; 2 – air heating system; HE – heating element stage

The operational principle of the module for investigation of the model artificial gas combustion process is based on the CO-N_2 mixture diffusion combustion in co-current high-temperature (up to 800°C) airflow. The module consists of a reaction chamber, air heating system and heating stages of the power control system.

In the experiment, the air temperature in the reaction zone is maintained at one of three levels:

- The first level is used in production gas turbines ($t_A = 400°C$);
- The second level is close to the reference CO-air ignition temperature ($t_A = 650°C$);
- The third level is achieved in practice with the self-contained air heating ($t_A = 800°C$).

The air and model artificial gas temperatures in the reaction zone, air, CO and N_2 flowrate at the flame ignition and extinction are recorded.

Table 1 presents the parameters of the reactive fluids in the reaction zone at the diffusion flame ignition.

Table 1. Diffusion flame ignition data.

№	V, L/min (at 20°C and 0,1 MPa)			t_A, °C	t_{CO-N_2}, °C
	Air	CO	N_2		
1	2.4	0.31	0.12	400	25
2	2.4	0.31	1.2	650	25
3	2.4	0.31	0.75	650	25
4	2.4	0.31	0.5	650	25
5	2.4	0.31	1.2	800	25
6	2.4	0.31	0.75	800	25
7	2.4	0.31	0.5	800	25

Table 2 presents the parameters of the reactive fluids in the reaction zone at the diffusion flame extinction.

Table 2. Diffusion flame extinction data.

№	V, L/min (at 20°C and 0,1 MPa)			t_A, °C	t_{CO-N_2}, °C
	Air	CO	N_2		
1	2.4	0.07	0.12	400	32
2	2.4	0.18	1.2	650	38
3	2.4	0.114	0.75	650	60
4	2.4	0.067	0.5	650	56
5	2.4	0.049	1.2	800	76
6	2.4	0.031	0.75	800	94
7	2.4	0.010	0.5	800	103

The extinction (lean blowoff) of a premixed fuel-air flames depends on the lower (LEL) and upper (UEL) explosive limits. The value of LEL is of great importance for the gas turbine combustion chamber operating regime in comparison with UEL.

Table 3 presents the LEL calculated values for a premixed CO-air flame in the temperature range of 100÷800°C.

Table 3 – Effect of the CO-air mixture temperature on the premixed flames LEL calculated values.

t_{CO-air}, °C	100	200	300	400	500	600	700	800
r^t_{LEL}, vol.%	10.380	9.498	8.616	7.734	6.852	5.970	5.088	4.207

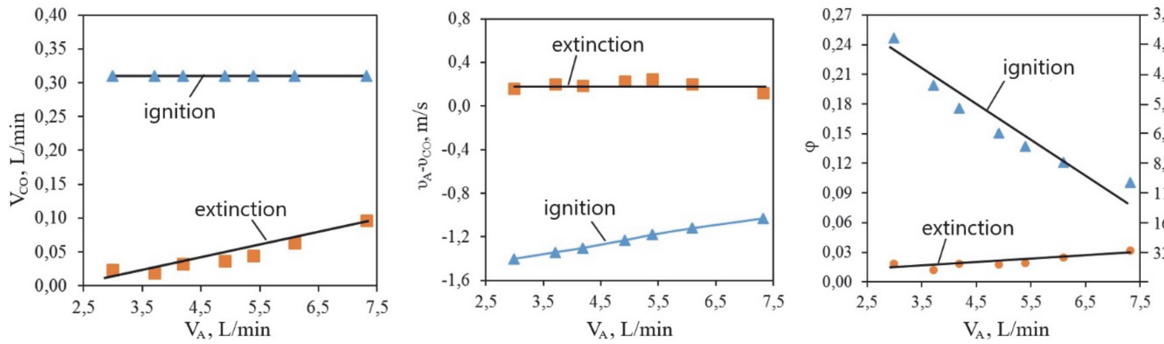
Equivalence fuel ratio φ characterizes the gas fuel and air flowrate in reaction zone:

$$\varphi = \frac{V_{CO}/V_A}{1/V^0} = \frac{1}{\alpha}$$

V_{CO}, V_A are CO and air volumetric flowrates in reaction zone, L/min (at 20°C and 0.1 MPa);
V^0 is theoretical air volumetric flowrate to complete combustion of 1 m^3 fuel gas, m^3/m^3;
α is the excess air coefficient.

3. Results

The gas flowrate at extinction is ~ 10÷30% of the initial flowrate and it increases with rising high-temperature air flowrate. The relationship between gas and air flowrates is of a linear character (figure 3).

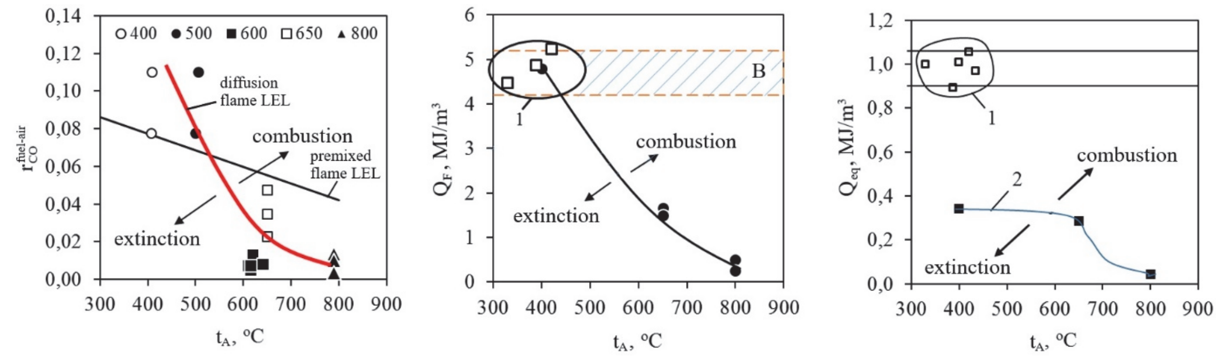


a) b) c)

Figure 3. Dependence of the CO flowrate (a), difference of the CO and air speeds (b) and the equivalence fuel ratio φ (c) on the air flowrate at the flame ignition and extinction.

The equivalence fuel ratio at flame ignition (φ_1) and in the steady combustion state decreases with a load from $\varphi_1 = 0.25$ to $\varphi_1 = 0.25$. The equivalence fuel ratio at flame extinction (φ_2) increases from $\varphi_2 = 0.013$ to $\varphi_2 = 0.032$ (figure 3).

The dependence of the CO minimum concentration $r_{CO}^{fuel-air}$ in the diffusion flame at the extinction limit on air temperature t_A has a characteristic appearance with a sharp fall as the temperature rises above 600 °C (figure 4a). As it can be seen, CO concentration $r_{CO}^{fuel-air}$ in the diffusion flame is lower than the calculated LEL value of premixed CO-air flame at air temperature above 500°C and the CO concentration $r_{CO}^{fuel-air}$ in the diffusion flame is higher than the calculated LEL value of premixed CO-air flame at air temperature higher than 500°C (figure 4).



a) b) c)

Figure 4. Effect of air temperature t_A on the $r_{CO}^{fuel-air}$ lower limit in the CO-air flame (a), on the Q_F (b) and Q_{eq} (c) lower limits in the CO-N_2-air diffusion flame: 1 – operating regime of the production artificial gas-fired CCPP; 2 – present experiment; Q_F – CO-N_2 mixture lower heating value; Q_{eq} – CO-N_2-air mixture equivalence lower heating value.

Increasing the air temperature to 800°C results in an increase in the combustion rate and expands the ignition limits in gas lower heating value by ~10÷20 times. The limiting lower heating value of the model artificial gas, at which the diffusion flame extinction occurs, reaches 0.248÷0.502 MJ/m^3 (at using high-temperature (800°C) air heating) instead of 4.803 MJ/m^3 in the normal operating regime of the production of artificial gas-fired CCPP (figure 4b).

The typical minimum lower heating values $\mathrm{Q_F}$ of artificial fuel gases before combustion in production of artificial gas-fired gas turbines are plotted in figure 4b (region B). As it can be seen, the experimental combustion chamber with standard heating of air and fuel gas does not operate on low-calorie gas of this composition without special devices that stabilize the fuel combustion in industrial gas turbine combustion chambers.

Equivalence lower heating value $\mathrm{Q_{eq}}$ of the CO-N_2-air mixture repeats qualitatively the curve for $\mathrm{r_{CO}^{fuel-air}}$. As it follows from figure 4c, the margin stability in equivalence lower heating value in the standard operating regime SOR ($t_\mathrm{A} = 400$ °C) is:

$$\frac{\left(\mathrm{Q_{eq}}\right)_{\mathrm{SOR}}}{\left(\mathrm{Q_{eq}}\right)_{\mathrm{extinction}}} \approx 3$$

$\mathrm{Q_{eq}}$ is equivalent lower heating value of the CO-N_2-air mixture:

$$\mathrm{Q_{eq}} = \frac{\mathrm{Q_F} \cdot \mathrm{V_{CO-N_2}}}{\mathrm{V_{CO-N_2}} + \mathrm{V_A}}$$

With an increase in air temperature to 800°C, the margin stability increases to ~10.

Conclusions

The LEL of the premixed and diffusion flames differs and depends on the air temperature.

An increase in the diffusion flame air temperature during combustion up to 800°C leads to:

- an increase in the rate of gas fuel combustion and expansion of the diffusion flame ignition LEL in terms of the lower heating value by ~10÷20 times;
- expansion of the flame extinction range in terms of the gas fuel critical lower heating value to 0.248÷0.502 MJ/m^3.

Acknowledgments

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